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Modeling of operation processes and reliability assurance of engineering machines under the multivariable time-varying random loading

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Abstract

The article describes the case of multivariable random loading, which occurs when the caterpillar suspension component acts as a set of loads of independent random processes. In the danger zone details of the changes in the components of the stress tensor are independent random processes. As an example of parts operating at such a loading the author discusses tracked vehicle road arm. Presently, there are no standard techniques for the estimatation of fatigue life under random multivariable loading currently available. The article describes the method of estimating the fatigue life for this type of load, based on the calculation of microplastic deformation. It uses a structural model of the material, based on the description of the deformation diagram of dependence by Ramberg-Osgood. To identify the model of accumulation of damage conventional mechanical and fatigue characteristics of the material were used. Accounting for natural dispersion of fatigue characteristics allowed to get the result as a function of the probability of failure-free operation. The validity of the approach is confirmed by comparing the calculation results with the experimental data. The practical application of the technique is illustrated by the example of predicting the durability and reliability of heavily loaded parts of the high-speed caterpillar vehicle.

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Keywords: Multivariable loading; Random process; Microplastic deformation; Structural model of the environment; Fatigue failure;

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1. Introduction

The competitiveness of engineering products is largely determined by the level of scientific and technical support for design activities, in particular by means of introduction into engineering of calculation-experimental methods to ensure machines reliability in the early stages of design.

The approach to the problem is illustrated by research processes of operational loading and the formation of fatigue damage of industrial tractor carrier system, as a part of the bulldozer [1 – 6].

2. Methods

The first phase of methodology implementation includes an analysis of force and kinematic processes obtained during field test of machines in various conditions. Figure 1, a, b shows an oscillogram of random loading process of T-10M tractor body caused by rig and ground during work as a bulldozer, cultivator and movement. Processing of oscillograms allows to classify investigated processes and determine their spectral characteristics and statistical characteristics (Fig. 2, a, b).

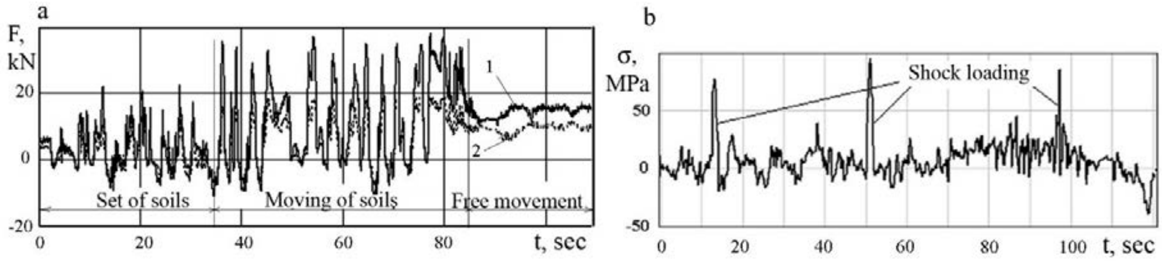

Fig.1. Experimental data: (a) the process of changing loads; (b) the process of changing stress.

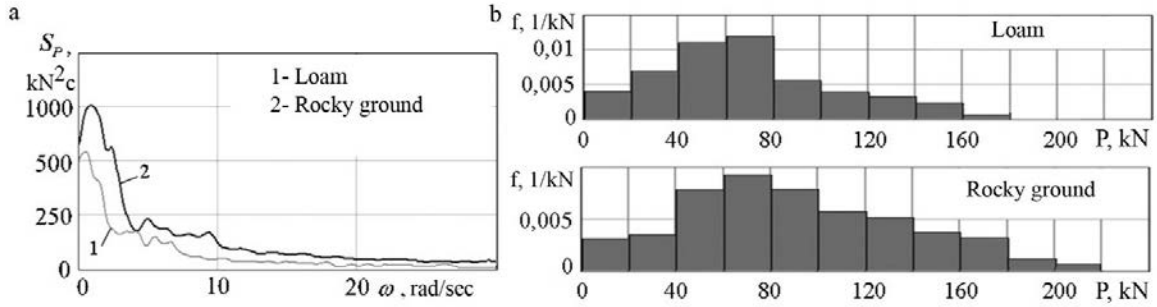

Fig.2. Statistical characteristics of loads: (a) the spectral density function, (b) the histogram peaks.

The field tests allowed to identify a number of special machine's operating modes and the corresponding mechanisms of interaction of its elements, such as:

1. Analysis of experimental data has revealed the cyclical load change during bulldozer work. This is due to technological process during which increasing amount of ground causes resistance and skidding increase and tractor's velocity drops. In order to prevent the tractor stop (extreme slippage) the driver needs lifting the blade every 5 ... 10 sec. The result is a cyclical loading, which becomes the main factor determining the fatigue life of parts and details of carrier system of the tractor.
2. Field tests have revealed the load mechanism of carriage system of the tractor as a random pulse stream (Fig. 1, b), due to semi-rigid suspension of industrial tractor in difficult conditions (working in a stone quarry, rolled back

at higher speeds, etc. .), where as a result of suspension strikes there is a abrupt redistribution of forces between the frame and its parts. This is fundamentally changing scheme of machine parts interaction, in particular, the case of the steering clutch operates in a cyclical changing of restrained torsion, which stress is 3-5 times higher than the value of the operating stress [7].

The second phase of the approach includes modeling of work of bulldozer and loosening unit. Peculiarities identified during field tests, particularly of dynamic processes, should be included in mathematic model, in particular:

- the existence of two coupled effects, the first is power effect by operating element and kinematic by chassis system;
- the significant non-linearity of a semi-rigid suspension system of the industrial tractor due to the variability of its structure;
- account of cyclical workloads associated with the phenomenon of extreme slippage of the bulldozer and other.

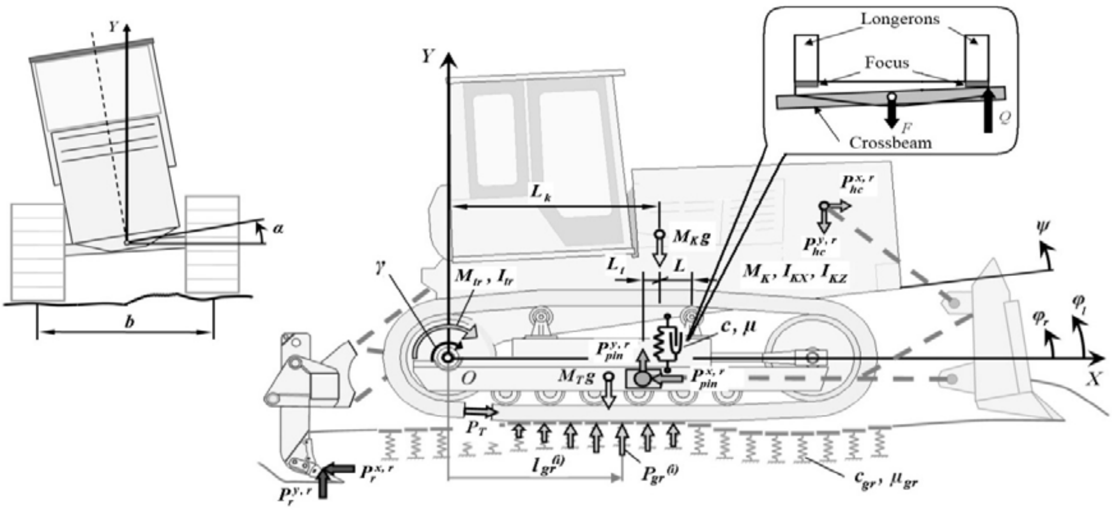

Fig.3. The diagram of a mathematical model.

Figure 3 shows a diagram of a mathematical model describing the dynamics of the tractor [8, 9]. The system of Lagrange differential equations for generalized coordinates $X, Y, \psi, \varphi_l, \varphi_r, \alpha, \gamma$:

$$\left(2M_T + M_K\right)\ddot{X} = P_{hc}^{x,r}(t) + P_{hc}^{x,l}(t) - P_{pin}^{x,r}(t) - P_{pin}^{x,l}(t) + P_T$$

$$M_T\left[2\left(\ddot{Y}+g\right)+0,5L_T\left(\ddot{\varphi}_l+\ddot{\varphi}_r\right)\right]+M_K\left[\ddot{Y}+g+0,5L_K\ddot{\psi}\right]=$$

$$=P_{pin}^{y,r}(t)+P_{pin}^{y,l}(t)-P_{hc}^{y,r}(t)-P_{yc}^{y,l}(t)+\sum_i P_{gr,r}^{(i)}(h)+\sum_i P_{gr,l}^{(i)}(h),$$

$$0,5M_K L_K\left[\ddot{Y}+g+0,5L_K\ddot{\psi}\right]+J_{K_z}\ddot{\psi}\;-cL^2\left[a/L+0,5\left(\varphi_l+\varphi_r\right)-\psi\right]-\mu L^2\left[0,5\left(\dot{\varphi}_l+\dot{\varphi}_r\right)-\dot{\psi}\right]=$$

$$=-\left(P_{hc}^{y,r}(t)+P_{hc}^{y,l}(t)\right)x_K-\left(P_{hc}^{x,r}(t)+P_{hc}^{x,l}(t)\right)y_K,$$

$$0,5M_T L_T\left[\ddot{Y}+g+0,5b\ddot{\alpha}+0,5L_T\ddot{\varphi}_l\right]+J_{T_z}\ddot{\varphi}_l\;+0,5cL^2\left[a/L+0,5\left(\varphi_l+\varphi_r\right)-\psi\right]+0,5\mu L^2\left[0,5\left(\dot{\varphi}_l+\dot{\varphi}_r\right)-\dot{\psi}\right]=$$

$$= P_{pin}^{y,l}(t)hx_T - P_{pin}^{x,l}(t)y_T + \sum_i P_{gr,l}^{(i)}(h)l_{gr}^{(i)} \ ,$$
$$0,5M_T L_T\left[\ddot{Y} + g - 0,5b\ddot{\alpha} + 0,5L_T\ddot{\varphi}_r\right] + J_{T_Z}\ddot{\varphi}_r + 0,5cL^2\left[a/L + 0,5\left(\varphi_l + \varphi_r\right) - \psi\right] + 0,5\mu L^2\left[0,5\left(\dot{\varphi}_l + \dot{\varphi}_r\right) - \dot{\psi}\right] =$$
$$= P_{pin}^{y,r}(t)x_T - P_{pin}^{x,r}(t)y_T + \sum_i P_{gr,r}^{(i)}(h)l_{gr}^{(i)} \ ,$$
$$M_T b\left[0,25L_T\left(\ddot{\varphi}_l - \ddot{\varphi}_r\right) + 0,5b\ddot{\alpha}\right] + \left[J_{K_X} + 2J_{T_X}\right]\ddot{\alpha} =$$
$$= 0,5b\left(P_{hc}^{y,r} + P_{pin}^{y,l} + \sum_i P_{gr,l}^{(i)}\left(h\right)\right) - 0,5b\left(P_{hc}^{y,l} + P_{pin}^{y,r} + \sum_i P_{gr,r}^{(i)}\left(h\right)\right), \qquad J_{pr}\ddot{\gamma} = M_{tr}i_{tr} - P_T r_{vk} \ ,$$

where, a is the static deflection of the housing under the weight of the tractor, J_{kx}, J_{kz} is the moments of inertia of the structure of the tractor about its center of gravity, I_{tx}, I_{tz} is the moments of inertia track roller relative to its center of gravity, Ipr is given to the drive wheel moment of inertia of the rotating masses and progressively moving the tractor engine and transmission, x_k, y_k, x_t, y_t is the coordinates of the attachment points of the hydraulic cylinder and dozer blade.

The system of differential equations integrated numerically with the help of a specially developed computer program.

At the third stage there is transformation of random generalized coordinates into loads acting on specific details of the construction [10, 11]. These processes are used as a initial data for finite element modeling and implementation of random processes and components of the stress tensor changes in potentially dangerous areas of structures [12, 13, 14].

Consistency between the calculated and experimental results is illustrated by the example of research of strength of T-10M tractor body steering clutches. According to mass operation, a significant reduction in the reliability of the tractor was due to the formation of fatigue cracks in the upper sheet body, leading to its depressurization, stiffness reduce and wear increase of transmission parts. Mathematic model accounting significant nonlinearity properties of semi-rigid suspension of industrial tractor revealed stress peaks of significant magnitude and frequency of the suspension in the area of origin of fatigue cracks.

Figure 4 shows the finite element model and distribution of equivalent stresses on the surface of the upper plate body of steering clutches in moment of shock loading in the suspension. Figure 5 shows pieces process of moving a caterpillar tractor across short high obstacles (movement in the stone quarry on collapsible soil). Comparison of the oscillograms obtained in field tests (Fig. 5, a) with a results of computer simulation (Fig. 5, b) confirms the adequacy of proposed mathematic models and the possibility of its use for predicting fatigue life of heavy-duty components of the machines.

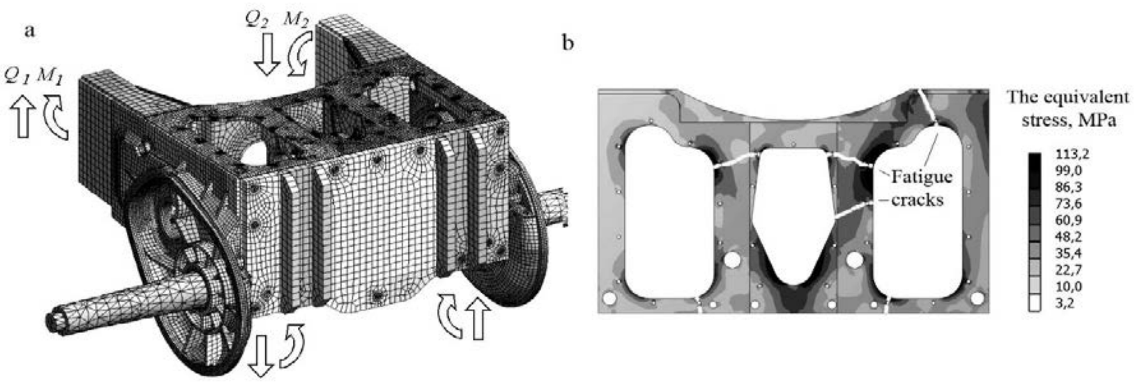

Fig.4. (a) the finite element model; (b) distribution of equivalent stresses.

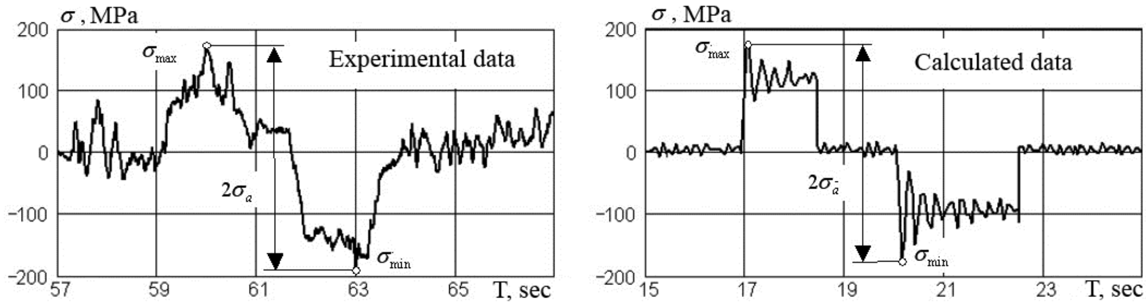

Fig.5. (a) the finite element model; (b) distribution of equivalent stresses.

The final stage involves predicting providing required service life for heavy duty elements of the carriage system according to the criterion of fatigue failure, for which the method of calculation of linear summation of damage was used [15, 9]. The calculation technique involves: account of changes of the components of the stress tensor with the help of complete cycles method [16, 17]; the calculation of equivalent amplitudes of stresses; determination of the law of distribution of equivalent amplitudes; parameter of loads input, and finally forecasting of the probability of failure-free function operation to the random nature of the loading and scattering of fatigue properties of materials [18, 19, 20]. The average predicted resource of the tractor steering clutches body provided by the proposed method is only 3100 hours (Fig. 6, a). This result agrees well with the data of the mass operation.

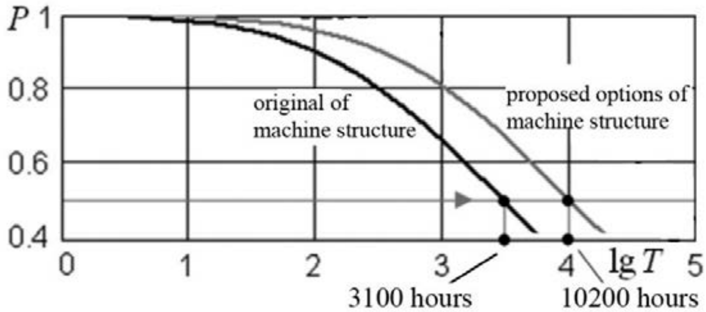

Fig.6. Functions of failure-free operation.

3. Conclusions

The effectiveness of the proposed approach is adjustment possibility of newly designed and modernized products, both at the stage of investigation of dynamic process, and at the stage of reasoned choice of materials and technology. For example, analysis of modeling results revealed that the increase the gap between the stops of equalizing beams and frame girders significantly reduces the magnitude and probability of stress peaks in the housing of steering clutches at the moment of impact in the suspension. Figure 6, a, b shows the function of failure-free operation for original and the proposed options of machine structure, which is predicting three-fold increase of average service life of steering clutches by the criterion of fatigue failure.

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